



RESEARCH LETTER

10.1002/2015GL064179

Key Points:

- Giant active lacustrine pockmarks are discovered in Lake Neuchâtel, Switzerland
- Pockmark activity is sustained by sublacustrine groundwater discharge
- Sediment record reveals episodic high-discharge phases

Supporting Information:

- Figures S1–S4, Table S1, and Text S1

Correspondence to:

A. Reusch,
anna.reusch@erdw.ethz.ch

Citation:

Reusch, A., et al. (2015), Giant lacustrine pockmarks with subaqueous groundwater discharge and subsurface sediment mobilization, *Geophys. Res. Lett.*, 42, doi:10.1002/2015GL064179.

Received 9 APR 2015

Accepted 15 APR 2015

Accepted article online 21 APR 2015

Giant lacustrine pockmarks with subaqueous groundwater discharge and subsurface sediment mobilization

Anna Reusch¹, Markus Loher^{1,2}, Damien Bouffard³, Jasper Moernaut^{1,4}, Franziska Hellmich², Flavio S. Anselmetti⁵, Stefano M. Bernasconi¹, Michael Hilbe⁵, Achim Kopf², Marvin D. Lilley^{1,6}, Gerrit Meinecke², and Michael Strasser¹

¹Geological Institute, ETH Zurich, Zürich, Switzerland, ²Marum Center for Marine Environmental Sciences, University of Bremen, Bremen, Germany, ³Margaretha Kamprad Chair, Physics of Aquatic Systems Laboratory, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, ⁴Facultad de Ciencias, Universidad Austral de Chile, Valdivia, Chile, ⁵Institute of Geological Sciences and Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland, ⁶School of Oceanography, University of Washington, Seattle, Washington, USA

Abstract Subsurface fluid flow in oceans and lakes affects bathymetric morphology, sediment distribution, and water composition. We present newly discovered giant lacustrine pockmarks in Lake Neuchâtel (up to 160 m diameter and 30 m deep) that rank among the largest known pockmarks in lakes. Our multidisciplinary study reveals ~60 m of suspended sediment inside a pockmark. The sediment suspension is 2.6° warmer and isotopically lighter in $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ by 1.5‰ than the ambient lake water, documenting currently active fluid flow by karstic groundwater discharge from the Jura Mountain front into the Swiss Plateau hydrological system. Strikingly, the levees of the pockmarks comprise subsurface sediment mobilization deposits representing episodic phases of sediment expulsion during the past. They strongly resemble subsurface fluid flow features in the marine realm. Comparable processes are expected to also be relevant for other carbonate-dominated mountain front ranges, where karstic groundwater discharges into lacustrine or marine settings.

1. Introduction

Mostly due to its remote underwater setting, advancement in our understanding of the interplay between subsurface fluid flow, fluid seepage, and the sediment record in the subaquatic environments is often limited by technological or logistical constraints to image and measure relevant features with sufficient spatial and temporal resolutions. In such settings, pockmarks and mud volcanoes are prominent features formed by fluid flow through the seabed, thereby venting gaseous or liquid fluids from the lithosphere into the hydrosphere [Hovland et al., 2002; Hovland and Judd, 1988; King and MacLean, 1970; Kopf, 2002]. A variety of fluids may form pockmarks: escaping interstitial gases [Solheim and Elverhøi, 1993], pore water seepage due to compression and overpressure [Harrington, 1985; Soter, 1999], and meteoric groundwater discharge [Canals et al., 1990; Colomer et al., 2002; Judd and Hovland, 2007; Morellón et al., 2014; Whitticar, 2002]. Pockmarks have been described from diverse marine geological environments [Hovland and Judd, 1988; Pilcher and Argent, 2007]. In freshwater systems, however, reports of pockmarks are scarce [Wessels et al., 2010], including only few recognized pockmark sites, e.g., as collapse structures of sublacustrine biogenic methane reservoirs [Bussmann et al., 2011; Wessels et al., 2010], in hydrothermally active environments or near active faults [Duck and Herbert, 2006; Pickrill, 1993; Ross et al., 2014], or subaquatic springs in karstic settings [Canals et al., 1990; Colomer et al., 2002; Matter et al., 2010]. The latter are often hypothesized to be a significant source for groundwater supply to lake systems, which in turn have an important role as water resources. Despite their recognized importance, locations and processes are rarely known or quantified [Morellón et al., 2014]. In this context, identifying the spatial distribution of seabed fluid expulsion features is crucial for understanding subsurface fluid pathways [Brothers et al., 2014].

Here we report the discovery of four giant pockmarks and associated deposits from subsurface sediment mobilization (SSM) in the deep waters (>100 m) of Lake Neuchâtel (Figure 1). In a multimethod approach, we combine geophysical, sedimentological, hydrological, geochemical, and geotechnical data in order to analyze the origin of the pockmarks. We present multiple lines of evidence supporting that the discovered circular, crater-shaped morphologic depressions are active pockmarks and test the hypotheses that these giant pockmarks are active gas seepage structures (Hypothesis I) or that they are sites of active groundwater inflow (Hypothesis II).

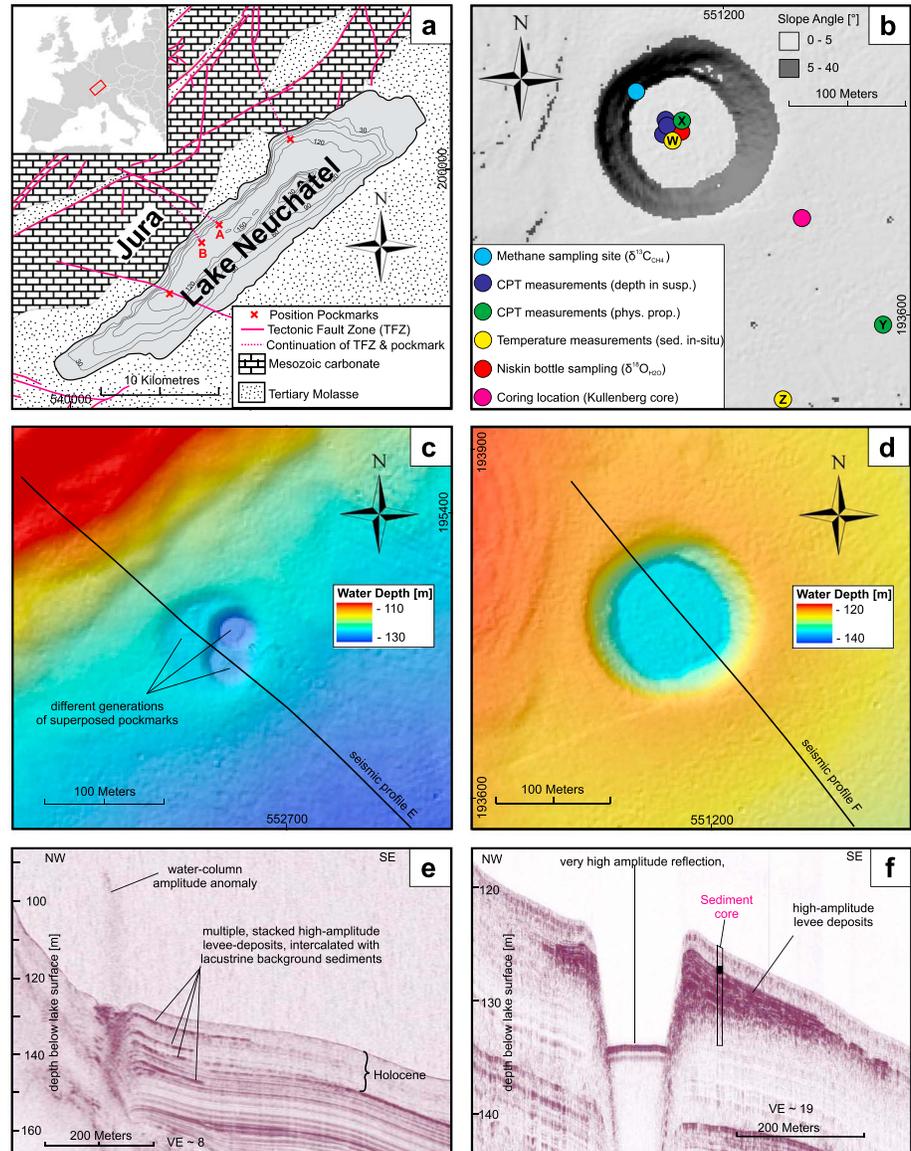


Figure 1. (a) Regional geological and tectonic map (modified after the Swiss tectonic map (1 : 500 000) [Swisstopo, the Swiss Federal Office of Topography, 2005]), including position of four large pockmarks ((A) “Treytel pockmark” and (B) “Chez-le-Bart pockmark”). Notice the position of the pockmarks aligned in the continuation of known tectonic fault zones. Coordinates are in meters (Swiss Grid, LV95). (b) Slope map of Chez-le-Bart pockmark with sampling stations of the different measurements inside the pockmark and at reference sites: methane sampling site (methane reference site in lake basin, outside of shown area); Cone Penetrometer Test (CPT) for measuring physical properties (green; X = inside pockmark, Y = reference site) (see Figure 2) and CPT sites for measuring depth within pockmark (dark blue); in situ temperature measurement site inside sediment (W = inside pockmark, Z = reference site) (see Figure 2 and Figure S2 in the supporting information); Niskin bottle sampling for $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ signal inside suspension within pockmark (red) and at the same position in the lake water column above the crater as reference site (red), coring location (Kullenberg sediment core, pink). Results are shown in Figure 2. (c) and (d): Multibeam-derived bathymetric maps showing (c) Treytel pockmark and (d) Chez-le-Bart pockmark. Indicated seismic profiles are shown underneath. (e) Seismic reflection profile (3.5 kHz pinger seismic) of Treytel pockmark, enhanced amplitude in water column. (f) Seismic reflection profile (subbottom profiler 5–15 kHz Chirp System), mounted on an autonomous underwater vehicle (AUV “Marum Seal”) of Chez-le-Bart pockmark. Inset shows sediment core (black area = shown core section Figure 2, for the location, see Figure 1b). Water depth calculated using sound velocity of 1450 m/s.

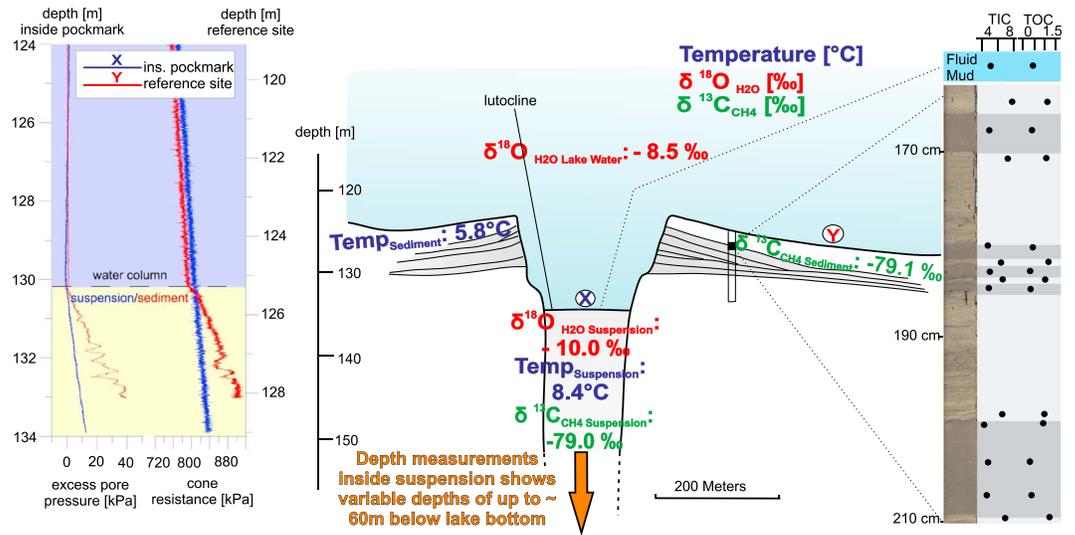


Figure 2. Data compilation of the Chez-le-Bart pockmark and reference sites (for the sampling stations, see Figure 1b). (left) Cone Penetrometer Test (CPT) data. (middle) Geochemical and in situ hydrological measurements at Chez-le-Bart pockmark. (right) Sediment core photograph with carbon data measured on the sediment core, and on a sediment sample of the fluidized sediment within the pockmark (light-blue: sediment sample of fluidized sediment inside Chez-le-Bart crater, light-grey: lacustrine background sediments, dark-grey: subsurface sediment mobilization deposits).

2. Study Area and Methods

Lake Neuchâtel (215 km² surface area, maximum water depth 153 m, volume 13.77 km³) is a glaciogenic lake and one of the largest freshwater basins in continental Europe [Portner, 1951; Schwalb, 1992]. It acts as an important water resource and is situated along the mountain front between the Jura Mountains and the western margin of the Swiss Molasse Basin (Figure 1a). The lake mostly lies within Oligocene-Miocene bedrock of clastic sediments belonging to the Upper Freshwater Molasse. In the northwestern part, the substrate partly consists of Mesozoic carbonates. The latter rise to the Jura Mountains immediately adjacent to the lake [Gorin et al., 2003; Ndiaye et al., 2014], which are known for their karst structures and numerous onshore springs [Guglielmetti et al., 2013; Perrin and Luetscher, 2008; Siegenthaler et al., 1983]. SW-NE trending tectonic folds and thrusts, as well as conjugate N-S and NW-SE trending strike-slip faults, characterize the bedrock geology, with one major dextral strike-slip fault zone running across Lake Neuchâtel [Gorin et al., 2003; Ibele, 2011; Meia, 1969; Mosar et al., 2008]. The giant pockmarks are exclusively situated on the foot of the northwestern slopes of Lake Neuchâtel, underlain by calcareous bedrock. Additionally, they occur in the continuation of known tectonic fault zones in the Jura Mountains, with one pockmark being directly aligned with the major strike-slip fault zone crossing the lake (Figure 1a). We have named the two pockmarks described here in detail after nearby localities—“Chez-le-Bart” pockmark and “Treytel” pockmark (Figure 1). Most of the measurements presented here were conducted at the Chez-le-Bart pockmark, ideally suited due to its size and apparent activity.

The pockmarks were discovered during a high-resolution swath bathymetry survey using a Kongsberg EM 2040 multibeam echo sounder (300 kHz, 1° beam width, 2 m grid). For further investigation and detailed characterization, we conducted comprehensive multitool and multisurvey lake campaigns. High-resolution seismic reflection profiles were acquired using a 3.5 kHz subbottom profiler (GeoAcoustic pinger source), as well as a deep-towed subbottom profiler (5–15 kHz Chirp System), which was mounted to an autonomous underwater vehicle (AUV marum seal 5000). Kullenberg-type sediment cores [Kelts et al., 1986] were retrieved for detailed sedimentological analysis of the immediate surroundings of the pockmarks. Niskin Bottles were used to sample the lake water as well as the material inside the Chez-le-Bart pockmark. Photographs were taken from the pockmark with the help of a remotely operated vehicle (ROV—see Figure S1 in the supporting information). Hydrological, geochemical, and geotechnical measurements were carried out at the Chez-le-Bart pockmark and at reference sites in order to characterize the sediment properties within the pockmark and to compare it to the reference sites (for the position of reference sites, see Figure 1b).

Temperature-logger tests were performed in order to study the in situ sediment temperatures. The temperature sensor was attached to a sediment-coring device in order to measure the in situ sediment temperature within 1 m sediment depth (see Figure 2 and Figure S2 in the supporting information for methodological details).

Isotopic analyses of methane and water were conducted on the sediment pore fluids. The origin of methane (microbial versus thermogenic) can be determined on the basis of the $\delta^{13}\text{C}_{\text{CH}_4}$ signals [Whiticar, 1999]. For this purpose, headspace methane samples were acquired according to the protocol of Matzinger *et al.* [2010] from short gravity-type sediment cores. Methane concentrations and $\delta^{13}\text{C}_{\text{CH}_4}$ values were determined using a gas chromatograph (Agilent 6890; column: GS-Carbonplot Agilent) and a mass spectrometer (Thermo Scientific Delta V Plus Isotope Ratio mass spectrometer) (see Figure S3 and Table S1 in the supporting information for methodological details). The oxygen isotope composition of the water ($\delta^{18}\text{O}_{\text{H}_2\text{O}}$) was determined by equilibration with CO_2 using a Gas Bench II (Thermo Fisher Scientific) coupled to a ConFlo IV interface and a Delta V Plus IRMS mass spectrometer. Selected samples were measured for total carbon (by combusting at 950°C in a CM5200 Autosamples Furnace, UIC Coulometrics) and total inorganic carbon (in a CM5130 Acidification module, UIC Coulometrics), coupled to a coulometer (CM5012 CO_2 Coulometer UIC Coulometrics).

Dynamic cone penetration testing (CPT) [Stegmann *et al.*, 2006a, 2006b] was used to geotechnically characterize the sediment inside the pockmark and at the reference site. The pore pressure measurements were further used to estimate the penetration depth of the CPT lance into the pockmark suspension and hence the depth of the pockmark itself (see Text S1 in the supporting information for methodological details).

3. Results

The four giant pockmarks discovered are crater-shaped morphological features with mostly circular shapes, diameters between 80 m and 160 m, and depths between 5.5 m and 30 m. Some of these morphologic depressions have a flat bottom. At Treytel pockmark, different generations of pockmarks morphologically superpose each other (Figure 1c). Furthermore, an amplitude anomaly is present in the seismic reflection data in the water column above the pockmark (Figure 1e). The material sampled from inside the Chez-le-Bart pockmark shows sediment in an unconsolidated and fluidized state: carbonate-rich clayey silt, with abundant detrital calcite and quartz grains. Thus, the flat bottom of the Chez-le-Bart pockmark represents a lutocline marking the top of sediments, which are held in suspension. This is further supported by geotechnical measurements that show a lower increase of cone resistance within the suspension inside the pockmark compared to values obtained in lacustrine background sediments at the reference site (Figure 2). The in situ pore pressure gradient is lower inside the sediment suspension (Figure 2). In seismic reflection data, the top of the suspension appears as a near-horizontal, high-amplitude seismic reflection, with no sedimentary structures visible below (Figure 1f). During the two years in which the lake campaigns took place, no change in depth of the lutocline within the seismic reflection data was observed. Several depth measurements with pore pressure sensors (CPT) inside the suspension reveal a maximum depth of ~ 60 m underneath the lutocline (Text S1 in the supporting information), thus 190 m below the lake surface. During several CPT deployments inside the pockmark, the total penetration depth underneath the lutocline ranges between ~ 20 and ~ 60 m, which shows variable topography of more consolidated sediment underlying the sediment suspension.

In-situ measured temperature of the fluidized sediment inside the pockmark is $\sim 8.4^\circ\text{C}$, while lake bottom water and sediment temperature at the reference site located at the same depth range are both $\sim 5.8^\circ\text{C}$. Compared to the reference site, the interstitial waters at the pockmark are thus $\sim 2.6^\circ\text{C}$ warmer.

In all sediment-core samples, methane is detected in generally low concentrations (in the range of $\mu\text{mol CH}_4/\text{ml}$ of sediment; see Figure 2 and Figure S3 in the supporting information). Methane concentrations in samples taken from the sediment suspension within the pockmark are below the detection limit. Over all samples, $\delta^{13}\text{C}_{\text{CH}_4}$ of methane range between -77.5‰ and -84.9‰ , which is characteristic of a microbial source of methane [Whiticar, 1999] (see Table S1 in the supporting information). Geochemical water analyses show clear differences between the suspension inside the pockmark and the lake water column: The $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ data of water samples in the water column above the pockmark show an average lake water signal of $-8.5\text{‰} \pm 0.02\text{‰}$, which fits very well with values of -8.7‰ to -8.4‰ , measured by Schwab [1992]. Interstitial waters of the fluidized sediment within the pockmark show an average value of $-10.0\text{‰} \pm 0.2\text{‰}$. The $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ values of the interstitial water within the pockmark are thus 1.5‰ lighter, compared to the lake water column.

Seismic reflection data show several distinct wedge-shaped high-amplitude seismic units intercalating the lacustrine background sediments in the subsurface around the pockmarks (Figure 1e), which have characteristic levee-type overspill geometries [Posamentier and Kolla, 2003]. Sediment cores reveal the levee deposits to be carbonate-bearing sediments with abundant detrital carbonate and quartz grains, ranging in size from clayey silt to fine sand. They are different from the surrounding lacustrine background sediments, which consist of massive calcareous clayey silt with abundant authigenic calcite and some siliciclastic components [Schwalb, 1992; Schwalb et al., 1994]. Photographs taken by an ROV show levee deposits outcropping at the inner rim of the pockmark (see Figure S1 in the supporting information). The levee deposits as well as the fluidized pockmark sediments consist of carbonate-bearing clayey silt with abundant siliciclastic components. Both sediments have lower carbonate values compared to the lacustrine background sediments (Figure 2).

4. Interpretation/Discussion

The pockmarks described here show distinct differences in dimension, morphology, and subsurface geology to pockmarks described in other lakes. They rank among the largest and deepest known pockmarks in lakes worldwide and are similar in dimension to marine pockmarks [Bussmann et al., 2011; Hovland et al., 2002; Hovland and Judd, 1988; Wessels et al., 2010]. The giant pockmarks in Lake Neuchâtel are characterized by distinct levee-type sediment-expulsion deposits, which document several phases of increased, explosive pockmark activity. The high-impedance contrast in seismic data of the flat bottom of the Chez-le-Bart pockmark is attributed to a lutocline, marking the interface between clear lake water and particle-rich material, which is kept in a dense suspension. This fluidized state of the sediment inside the pockmark is shown by geotechnical in situ tests and by sediment samples from inside the pockmark. An active mechanism is needed to keep the sediment inside the pockmark in suspension.

Active mechanisms such as fluid flow from the subsurface are driving mechanism for keeping the sediment in suspension. In this geological environment, two mechanisms are plausible which commonly create and maintain pockmarks: gas flow (microbial or thermogenic) or liquid flow (e.g., groundwater) [Bussmann et al., 2011; Hovland et al., 2002; Judd and Hovland, 2007]. In the following sections, we discuss our data with respect to these two hypotheses: Hypothesis I: the pockmarks are active gas seepage structures, as inferred from the amplitude anomaly within the water column, which could potentially represent a gas flare (Figure 1e), and Hypothesis II: they represent active groundwater seepage sites, where groundwater—possibly from the Jura Mountain karst system—flows into the lake.

Measured methane concentrations inside the two studied pockmarks and at the reference site are generally low. Isotopic signatures of methane indicate that the gas in the sediment is of a microbial nature, i.e., young gas related to microbial respiration within the lake sediments. The methane concentration profiles do not indicate active gas flow. However, at pockmarks originating from microbial methane seepage in Lake Constance, it was observed that sediment inside the pockmark had almost the same methane concentration as a reference site outside the pockmark, even though pockmark activity was verified by observed bubble release [Bussmann et al., 2011]. Therefore, the involvement of gas seepage (microbial or thermogenic) cannot be completely excluded and may play a more important role during times of enhanced pockmark activity.

A potential explanation of the observed reflection amplitude anomaly in the water column above Treytel pockmark can either be explained by a water mass with different physical properties, a gas flare, or a frequently observed accumulation of fish above pockmarks. This has been described before and was related to upwelling of nutrient-rich waters near pockmarks [Dando et al., 1991; Hammer et al., 2009; Judd and Hovland, 2007; Karpen et al., 2006].

Temperature measurements were performed in order to investigate potential signs for groundwater inflow such as temperature anomalies: Bottom water temperatures in water depths greater than 100 m typically show values between 5°C and 6°C all year round at the study site [Lambert, 1997; Schwalb, 1992]. Karstic waters typically show the regional annual mean temperature [Jeannin, 1989; Luetscher and Jeannin, 2004]—in this area: 9–10°C [Jornod, 1991]. Temperature measurements at close-by karst springs onshore show mean values of 8.8°C [Mathey, 1976]. Bottom water temperature measurements in the lake, as well as in situ sediment temperatures at the reference site in the basin, show temperatures of 5.8°C. However, temperature measurements within the sediment

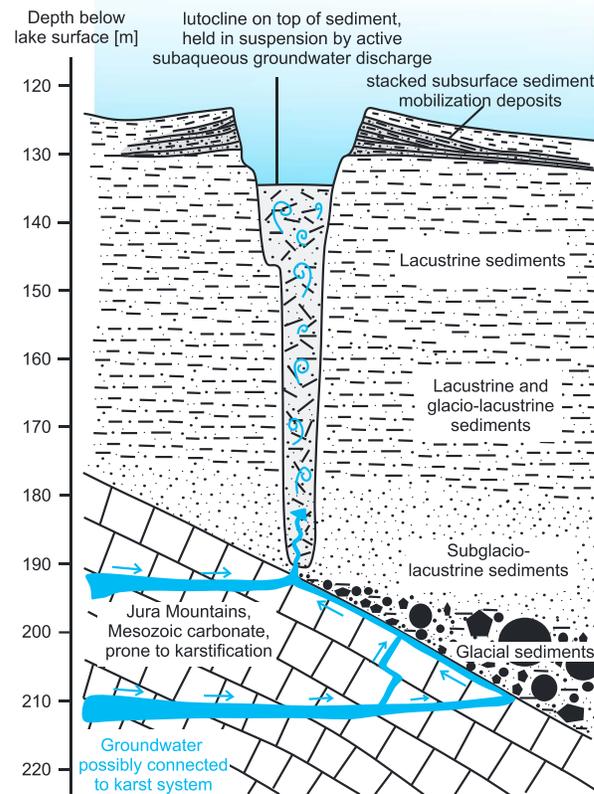


Figure 3. Conceptual model of Chez-le-Bart pockmark. Sedimentary units interpreted after *Ndiaye et al.* [2014], and references therein.

suspension inside the pockmark show values of 8.4°C , which are well within the temperature range of the internal Jura karst system. Compared to the reference site, the fluid inside the pockmark is $\sim 2.6^{\circ}\text{C}$ warmer. The large temperature difference strongly hints at a different water source within the pockmark, compared to the lake water, thus supporting the hypothesis of inflowing groundwater.

This result is further supported by the differences measured in $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ signals in water samples that can be used to reveal the presence of different water masses [Assayag et al., 2008; Dinçer, 1968]: $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ analysis of water samples reveals a 1.5‰ lighter interstitial water inside the pockmark, compared to the ambient water. The different $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ signals clearly indicate two different water masses, with the isotopically lighter and warmer water most likely being karstic groundwater. This interpretation is justified by data from *Siegenthaler et al.* [1983] that documented $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ signals of karstic springs in the hinterland of Lake Neuchâtel to be in the range of -10‰ to -11‰ , thus fitting well to the values measured in the interstitial waters within the pockmark ($\delta^{18}\text{O}_{\text{H}_2\text{O}} \text{ pockmark} = -10.0\text{‰} \pm 0.2\text{‰}$).

In combination, our findings of the geophysical and geotechnical surveys (60 m of fluidized sediment below the lutocline), the hydrological measurements (2.6°C temperature difference), and geochemical analysis (difference of 1.5‰ in $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ signals) clearly document that the Chez-le-Bart pockmark is currently active and fed by karstic groundwater entering the lake as focused fluid flow through the subsurface sediments. In other terms, the Chez-le-Bart pockmark acts as a sublacustrine spring. This interpretation can likely be extrapolated to the other giant pockmarks discovered in the course of this study, which are also exclusively located on the Jura side of Lake Neuchâtel, and seemingly aligned with known tectonic fault zones (Figure 1a), which likely serve as conduits for karstic water due to enhanced permeability [Häuselmann et al., 1999].

In order to further explore potential fluid pathways and flow processes through the subsurface, we correlate the CPT-derived maximum depth of the pockmark (at 190 m below lake surface at the Chez-le-Bart pockmark) with the seismic stratigraphic interpretation from air gun seismic reflection data by *Clerc* [2006], *Gorin et al.* [2003], and *Ndiaye et al.* [2014]. This correlation suggests that the pockmark is located where the glacial sediments onlap onto the Mesozoic carbonate that rise to form the Jura Mountains on the NW side of the lake. We suggest that pathways for groundwater flow, driven by elevated hydraulic head from the elevated Jura mountain where karst infiltration occurs, may preferentially develop at boundaries between the glacial sediments and the bedrock, as well as the postglacial lacustrine sediments, which typically mark a high-permeability contrast boundary in the subsurface of Swiss lakes [Strasser et al., 2007] (Figure 3). Our model and data imply a significant contribution of subsurface fluid flow to the exchange of water from the Jura Mountains to the Swiss Plateau.

A striking result of our study is the correlation of high-amplitude, wedge-shaped reflections in the seismic data with the distinct levee-type sediments in the core data that show clear similarities in all measured parameters with the fluidized sediment inside the pockmark. We interpret these deposits to have resulted from sediment mobilization within the pockmark and subsequent sediment expulsion on the lake floor.

Therefore, we refer to these deposits as subsurface sediment mobilization (SSM) deposits [Van Rensbergen *et al.*, 2003]. The SSM deposits at the giant pockmarks in Lake Neuchâtel show a high resemblance to “homogenites,” associated with sublacustrine karst springs in Lago Banyoles [Morellón *et al.*, 2014 and references therein]. At the Treytel pockmark, four prominent seismic reflections correlated to SSM deposits are imaged within the postglacial seismic-stratigraphic sequence (Figure 1e). They show a strong similarity to a phenomenon known from the subsurface of mud volcanoes—so-called “Christmas-tree structures” [Kopf, 2008; Somoza *et al.*, 2003]—and are clear evidence for repeated, punctuated pockmark-expulsion phases.

Furthermore, swath bathymetry data reveal several generations of superposed pockmarks (Figure 1c), further indicating repeated pulses of sediment fluidization, consolidation, and refluidization. Also, in our sediment cores, SSM deposits are intercalated with lacustrine background sediments. Together, these results lead us to conclude that fluid from below must have fluidized and expanded the sediments, raised the lutocline and expelled the sediments on the lake floor during distinct times in the past.

The active groundwater flow as seen today at the Chez-le-Bart pockmark does not result in active sediment expulsion and has not done so for ~1600 years (as estimated based on mean sedimentation rates after Schwab *et al.* [1998] and thickness of background sediment overlying the top of the youngest SSM deposit). It remains unclear whether the sediments within the pockmark reconsolidated between expulsion events or remained in a fluidized state as can be observed nowadays at the Chez-le-Bart pockmark.

Long-term variability (as successfully monitored on offshore pockmarks in Greece by Marinaro *et al.* [2007]) as well as the driving mechanisms for activation and cessation (e.g., driven by changes in the hydraulic head, possibly triggered by heavy precipitation as shown on sublacustrine karst springs in Spain by Morellón *et al.* [2014], strong snowmelt, and earthquakes) of sediment expulsion phases need further investigation and potentially will allow testing of yet-unresolved hypotheses for likewise global settings.

5. Conclusion

Multiple-tool geophysical and geological data revealed the presence of some of the largest ever reported lacustrine pockmarks on the subaquatic toe-of-slope (>100 m water depth) of Lake Neuchâtel. We show that the sediment inside the largest pockmark is held in suspension, indicating currently active fluid flow. Geochemical pore fluid analyses show no indications of current gas seepage. Elevated temperature values and depleted $\delta^{18}\text{O}$ signals within the pockmark indicate active sublacustrine groundwater discharge from the Jura karst system across the mountain front into the hydrological system of the Swiss Plateau, entering the lake as focused fluid flow through the pockmark. While our data do not allow for conclusive rejection of our first hypothesis (gas), all our results clearly support the second hypothesis (groundwater seepage) and document that groundwater—likely karstic water—is actively maintaining the giant pockmark.

The levees of the pockmarks are characterized by subsurface sediment mobilization deposits intercalating the background sediments, which represent episodic sediment expulsion phases throughout the past. The newly discovered giant pockmarks allow studying in detail subsurface sediment mobilization, which is—due to the ever-increasing resolution of subsurface data—more and more being shown to play an important role within the terrestrial hydrological system as well as within the marine realm [Van Rensbergen *et al.*, 2003].

An analysis of conditions suitable for subaqueous groundwater flow development shows that the type of pockmark we studied may be quite widespread. Comparable processes must also be relevant for other mountain front ranges and coastal mountain ranges, where groundwater flow may discharge into lacustrine and marine settings [Fleury *et al.*, 2007] and where yet-undiscovered subaqueous springs can explain negative groundwater budgets. Knowledge about processes that determine the water quality, such as sediment fluidization events [Colomer *et al.*, 2002], is fundamental, as lake systems and karst aquifers play an important role as water resources [Fleury *et al.*, 2007]. A major implication of our study is the geophysical multidisciplinary approach in investigating subsurface fluid flow, associated pockmarks and subsurface sediment mobilization deposits in detail, which elsewhere is often limited by technological or logistical constraints to image and measure relevant features with sufficient resolution.

Acknowledgments

Data supporting Figure 2 are available as in supporting information. We thank Robert Hofmann, Reto Seifert, Stewart Bishop, Adrian Gilli, Alfred Johny Wüest, and many others for their help during the lake surveys. We thank the lake police (Canton Vaud) for the ROV survey. Pierre-Yves Jeannin, Urs Eichenberger, and Sebastian Breitenbach are thanked for consultancy on Jura karst processes. Katrina Kremer and Michael Strupler are thanked for constructive comments on this manuscript. This work was supported by Swiss National Science Foundation grant PP00P2_133481.

The Editor thanks Ulf Mallast and two anonymous reviewers for their assistance in evaluating this paper.

References

- Assayag, N., D. Jézéquel, M. Ader, E. Viollier, G. Michard, F. Prévot, and P. Agrinier (2008), Hydrological budget, carbon sources and biogeochemical processes in Lac Pavin (France): Constraints from $\delta^{18}\text{O}$ of water and $\delta^{13}\text{C}$ of dissolved inorganic carbon, *Appl. Geochem.*, *23*(10), 2800–2816.
- Brothers, D. S., C. Ruppel, J. W. Kluesner, U. S. ten Brink, J. D. Chaytor, J. C. Hill, B. D. Andrews, and C. Flores (2014), Seabed fluid expulsion along the upper slope and outer shelf of the U.S. Atlantic continental margin, *Geophys. Res. Lett.*, *41*, 96–101, doi:10.1002/2013GL058048.
- Bussmann, I., S. Schloemer, M. Schlueter, and M. Wessels (2011), Active pockmarks in a large lake (Lake Constance, Germany): Effects on methane distribution and turnover in the sediment, *Limnol. Oceanogr.*, *5*(1), 317–393.
- Canals, M., H. Got, R. Julia, and J. Serra (1990), Solution-collapse depressions and suspensates in the limnocratic lake of Banyoles (NE Spain), *Earth Surf. Processes Landforms*, *15*(3), 243–254.
- Clerc, N. (2006), Etude du remplissage sédimentaire quaternaire du lac de Neuchâtel (Suisse) par sismique réflexion à haute résolution. Contribution à la géologie glaciaire, Diplôme thesis, Université de Genève, Geneva, Switzerland.
- Colomer, J., T. Serra, M. Soler, and X. Casamitjana (2002), Sediment fluidization events in a lake caused by large monthly rainfalls, *Geophys. Res. Lett.*, *29*(8), 1260, doi:10.1029/2001GL014299.
- Dando, P., M. Austen, R. Burke Jr., M. Kendall, M. Kennicutt II, A. Judd, D. Moore, S. O'Hara, R. Schmaljohann, and A. Southward (1991), Ecology of a North Sea pockmark with an active methane seep, *Mar. Ecol. Prog. Ser.*, *70*, 49–63.
- Diñçer, T. (1968), The use of oxygen 18 and deuterium concentrations in the water balance of lakes, *Water Resour. Res.*, *4*(6), 1289–1306, doi:10.1029/WR004i006p01289.
- Duck, R. W., and R. A. Herbert (2006), High-resolution shallow seismic identification of gas escape features in the sediments of Loch Tay, Scotland: Tectonic and microbiological associations, *Sedimentology*, *53*(3), 481–493.
- Flury, P., M. Bakalowicz, and G. de Marsily (2007), Submarine springs and coastal karst aquifers: A review, *J. Hydrol.*, *339*(1–2), 79–92.
- Gorin, G., D. Morend, and A. Pugin (2003), Bedrock, Quaternary sediments and recent fault activity in central Lake Neuchâtel, as derived from high-resolution reflection seismics, *Eclogae Geol. Helv.*, *96*, S3–S10.
- Guglielmetti, L., F. Negro, G. Mauri, F.-D. Vuataz, Y. Abdelfettah, N. Clerc, N. Giroud, L. Marguet, and E. Schill (2013), GeoNE: An integrated project for the exploration of low enthalpy deep aquifers in the canton of Neuchâtel, western Switzerland, in *European Geothermal Congress*, Pisa, Italy.
- Hammer, Ø., K. Webb, and D. Depreiter (2009), Numerical simulation of upwelling currents in pockmarks, and data from the Inner Oslofjord, Norway, *Geo Mar. Lett.*, *29*(4), 269–275.
- Harrington, P. K. (1985), Formation of pockmarks by pore-water escape, *Geo Mar. Lett.*, *5*(3), 193–197.
- Häuselmann, P., P.-Y. Jeannin, and T. Bitterli (1999), Relationships between karst and tectonics: Case-study of the cave system north of Lake Thun (Bern, Switzerland), *Geodin Acta*, *12*(6), 377–388.
- Hovland, M., and A. Judd (1988), *Seabed Pockmarks and Seepages: Impact on Geology, Biology and Marine Environments*, Graham and Trotman, London.
- Hovland, M., J. V. Gardner, and A. G. Judd (2002), The significance of pockmarks to understanding fluid flow processes and geohazards, *Geofluids*, *2*(2), 127–136.
- Ibele, T. (2011), Tectonics of the Western Swiss molasse basin during Cenozoic times, PhD thesis, Université de Fribourg, Fribourg, Switzerland.
- Jeannin, P.-Y. (1989), *Paramètres Physico-chimiques Des Eaux Dans le Karst*, Centre d'hydrogéologie de l'Université de Neuchâtel, Switzerland.
- Jornod, G. (1991), Observations météorologiques faites en 1990 à l'Observatoire cantonal de Neuchâtel, *Bull. Soc. Neuchâtel. Sci. Nat.*, *114*, 149–156.
- Judd, A., and M. Hovland (2007), *Seabed Fluid Flow: The Impact on Geology, Biology, and the Marine Environment*, Cambridge Univ. Press, Cambridge.
- Karpen, V., L. Thomsen, and E. Suess (2006), Groundwater discharges in the Baltic Sea: Survey and quantification using a schlieren technique application, *Geofluids*, *6*(3), 241–250.
- Kelts, K., U. Briegel, K. Ghilardi, and K. Hsu (1986), The limnogeology-ETH coring system, *Schweiz. Z. Hydrol.*, *48*(1), 104–115.
- King, L., and B. MacLean (1970), Pockmarks on the Scotian Shelf, *Geol. Soc. Am. Bull.*, *81*(10), 3141–3148.
- Kopf, A. J. (2002), Significance of mud volcanism, *Rev. Geophys.*, *40*(2), 1005, doi:10.1029/2000RG000093.
- Kopf, A. J. (2008), Volcanoes: Making calderas from mud, *Nat. Geosci.*, *1*(8), 500–501.
- Lambert, P. (1997), La sédimentation dans le Lac de Neuchâtel (Suisse) processus actuels et reconstitution paléoenvironnementale de 1500 BP à nos jours, PhD thesis, Université de Neuchâtel, Neuchâtel, Switzerland.
- Luetscher, M., and P.-Y. Jeannin (2004), Temperature distribution in karst systems: The role of air and water fluxes, *Terra Nova*, *16*(6), 344–350.
- Marinero, G., et al. (2007), A cabled monitoring module for gas seepage: The first experiment in a pockmark (Patras Gulf, Greece), paper presented at Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies, 2007. Rome, Italy, 434–438.
- Mathey, B. (1976), Hydrogéologie des bassins de la Serrière et du Seyon (Neuchâtel, Suisse), PhD thesis, Université de Neuchâtel, Neuchâtel, Switzerland.
- Matter, M., F. S. Anselmetti, B. Jordanoska, B. Wagner, M. Wessels, and A. Wuest (2010), Carbonate sedimentation and effects of eutrophication observed at the Kalistamsubaquatic springs in Lake Ohrid (Macedonia), *Biogeosciences*, *7*, 3755–3767.
- Matzinger, A., B. Mueller, P. Niederhauser, M. Schmid, and A. Wuest (2010), Hypolimnetic oxygen consumption by sediment-based reduced substances in former eutrophic lakes, *Limnol. Oceanogr.*, *55*(5), 2073–2084.
- Meia, J. (1969), Géologie du Mont Aubert et de l'anticlinal Soliat-Montagne de Boudry au nord du Lac de Neuchâtel, PhD thesis, Université de Neuchâtel, Neuchâtel, Switzerland.
- Morellón, M., F. S. Anselmetti, B. Valero-Garcés, S. Giral, D. Ariztegui, A. Sáez, M. P. Mata, F. Barreiro-Lostres, M. Rico, and A. Moreno (2014), The influence of subaquatic springs in lacustrine sedimentation: Origin and paleoenvironmental significance of homogenites in karstic Lake Banyoles (NE Spain), *Sediment. Geol.*, *311*, 96–111.
- Mosar, J., T. Ibele, and E. Matzenauer (2008), Tectonics of the Moasse Basin of Western Switzerland: An Overview *Rep.*, nagra report, 102 pp, Wetting, Switzerland.
- Ndiaye, M., N. Clerc, G. Gorin, S. Girardclos, and J. Fiore (2014), Lake Neuchâtel (Switzerland) seismic stratigraphic record points to the simultaneous Würmian deglaciation of the Rhône Glacier and Jura Ice Cap, *Quat. Sci. Rev.*, *85*, 1–19.
- Perrin, J., and M. Luetscher (2008), Inference of the structure of karst conduits using quantitative tracer tests and geological information: Example of the Swiss Jura, *Hydrogeol. J.*, *16*(5), 951–967.
- Pickrill, R. A. (1993), Shallow seismic stratigraphy and pockmarks of a hydrothermally influenced lake, Lake Rotoiti, New Zealand, *Sedimentology*, *40*(5), 813–828.

- Pilcher, R., and J. Argent (2007), Mega-pockmarks and linear pockmark trains on the West African continental margin, *Mar. Geol.*, *244*(1–4), 15–32.
- Portner, C. (1951), La formation du sédiment calcaire du lac de Neuchâtel, *Schweiz. Z. Hydrol.*, *13*(2), 199–290.
- Posamentier, H. W., and V. Kolla (2003), Seismic geomorphology and stratigraphy of depositional elements in deep-water settings, *J. Sediment. Res.*, *73*(3), 367–388.
- Ross, K. A., B. Smets, M. De Batist, M. Hilbe, M. Schmid, and F. S. Anselmetti (2014), Lake-level rise in the late Pleistocene and active subaquatic volcanism since the Holocene in Lake Kivu, East African Rift, *Geomorphology*, *221*, 274–285.
- Schwalb, A. (1992), Die Sedimente des Lac de Neuchâtel (Schweiz): Rekonstruktion spät- und postglazialer Klima- und Umweltveränderungen, PhD thesis, Univ. of Neuchâtel, Neuchâtel, Switzerland.
- Schwalb, A., G. Lister, and K. Kelts (1994), Ostracode carbonate $\delta^{18}\text{O}$ - and $\delta^{13}\text{C}$ -signature of hydrological and climatic changes affecting Lake Neuchâtel, Switzerland, since the latest Pleistocene, *J. Paleolimnol.*, *11*(1), 3–17.
- Schwalb, A., P. Hadorn, N. Thew, and F. Straub (1998), Evidence for Late Glacial and Holocene environmental changes from subfossil assemblages in sediments of Lake Neuchâtel, Switzerland, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *140*(1–4), 307–323.
- Siegenthaler, U., U. Schotterer, and I. Mueller (1983), Isotopic and chemical investigations of springs from different karst zones in the Swiss Jura, in *Isotope Hydrology 1983*, pp. 153–172, IAEA, Vienna.
- Solheim, A., and A. Elverhøi (1993), Gas-related sea floor craters in the Barents Sea, *Geo Mar. Lett.*, *13*(4), 235–243.
- Somoza, L., et al. (2003), Seabed morphology and hydrocarbon seepage in the Gulf of Cádiz mud volcano area: Acoustic imagery, multibeam and ultra-high resolution seismic data, *Mar. Geol.*, *195*(1–4), 153–176.
- Soter, S. (1999), Macroscopic seismic anomalies and submarine pockmarks in the Corinth–Patras rift, Greece, *Tectonophysics*, *308*(1–2), 275–290.
- Stegmann, S., T. Mörz, and A. Kopf (2006a), Initial results of a new Free Fall-Cone Penetrometer (FF-CPT) for geotechnical in situ characterisation of soft marine sediments, *Norw. J. Geol.*, *86*(3), 199–208.
- Stegmann, S., H. Villinger, and A. Kopf (2006b), Design of a modular, marine free-fall cone penetrometer, *Sea Technol.*, *47*(2), 27–33.
- Strasser, M., S. Stegmann, F. Bussmann, F. S. Anselmetti, B. Rick, and A. Kopf (2007), Quantifying subaqueous slope stability during seismic shaking: Lake Lucerne as model for ocean margins, *Mar. Geol.*, *240*(1–4), 77–97.
- Swisstopo, the Swiss Federal Office of Topography (2005), Tectonic map of Switzerland 1:500 000, Swisstopo, Wabern, Switzerland.
- Van Rensbergen, P., R. R. Hillis, A. J. Maltman, and C. K. Morley (2003), Subsurface sediment mobilization: Introduction, *Geol. Soc. London, Spec. Publ.*, *216*(1), 1–8.
- Wessels, M., I. Bussmann, S. Schloemer, M. Schlueter, and V. Böder (2010), Distribution, morphology, and formation of pockmarks in Lake Constance, Germany, *Limnol. Oceanogr.*, *55*(6), 2623–2633.
- Whiticar, M. J. (1999), Carbon and hydrogen isotope systematics of bacterial formation and oxidation of methane, *Chem. Geol.*, *161*(1–3), 291–314.
- Whiticar, M. J. (2002), Diagenetic relationships of methanogenesis, nutrients, acoustic turbidity, pockmarks and freshwater seepages in Eckernförde Bay, *Mar. Geol.*, *182*(1–2), 29–53.